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Report under

Contract 1083P0015-35

**STUDY
OF SPACE CHARGE-DOMINATED BEAM BUNCHING
AND
SOME ASPECTS OF SSF LINAC DESIGNS**

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INTRODUCTION

This report is made up from works under the Agreement # 1083P0015-35 between Los Alamos National Laboratory and Moscow Radiotechnical Institute. There are five report parts. In the 1-st, 2-nd, and 3-d parts works on SCD-beam dynamics understanding (started in [1-5]) were continued. In the 4-th and 5-th parts two conceptual linac designs were considered: for deuteron linac with energy of 40 MeV and for proton linac with energy 1 GeV. The both linacs have focusing by superconducting solenoids (SSF linacs). The 1 GeV proton CW linac design is an extension of the design from [4].

I

**BUNCHING PROCESS ANALYTICAL INVESTIGATION
FOR SPACE CHARGE-DOMINATED BEAM**

**1.1. Space Charge Fields for Beams
with Periodical Charge Distributions**

Let us consider beam of infinite length and axial symmetry which has velocity v and flows inside an infinite cylindrical channel with radius R_a . Current flow $I(r, z)$ repeat periodically along longitudinal axis z with period L .

The potential distribution for beam with flow density $\rho(r, z)$ is determined from Poisson equation

$$\frac{\partial U}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial U}{\partial r} \right) = - \frac{1}{\epsilon_0} \rho(r, z) \quad (1)$$

with boundary conditions

$$dU/dr(0, z) = 0, \quad U(r, 0) = U(r, L), \quad U(R_a, z) = 0. \quad (2)$$

Charge density can be considered as

$$\rho(r, z) = \frac{I}{\pi R_a^2 v} \tilde{\rho}(r, z)$$

where I is mean current, $\tilde{\rho}(r, z)$ - unitless form factor for charge distribution.

The transfer of variables in equations (1) - (2) to unitless ones $\Psi = 2\pi z/L$ and $\tilde{r} = r/R_a$ leads to equation (3)

$$\frac{\partial^2 U}{\partial \Psi^2} \left(\frac{2\pi R_a}{L} \right)^2 + \frac{1}{\tilde{r}} \left(\tilde{r} \frac{\partial \tilde{U}}{\partial \tilde{r}} \right) = \frac{I}{\pi \epsilon v} \tilde{\rho}(\tilde{r}, \Psi) \quad (3)$$

The general form of equation (3) shows that the form of

potential distribution depends only on value of R_a/L if the form of charge distribution is the same. The voltage value is proportional to $\kappa = I/(\pi\epsilon V)$.

In its turn $U(\tilde{r}, \Psi)$ can be presented as

$$U(\tilde{r}, \Psi) = \frac{I}{\pi\epsilon V} \tilde{U}(\tilde{r}, \Psi)$$

Then for U there is equation

$$\frac{\partial^2 \tilde{U}}{\partial \Psi^2} \left(\frac{2\pi R_a}{L} \right)^2 + \frac{1}{\tilde{r}} \left(\tilde{r} \frac{\partial \tilde{U}}{\partial \tilde{r}} \right) = - \tilde{\rho}(\tilde{r}, \Psi) \quad (4)$$

with boundary conditions

$$\partial U / \partial r(0, \Psi) = 0, \quad U(\tilde{r}, 0) = U(\tilde{r}, 2\pi), \quad U(1, \Psi) = 0 \quad (5)$$

Periodical function $\tilde{\rho}(\tilde{r}, \Psi)$ can be expanded into a Fourier series

$$\tilde{\rho}(\tilde{r}, \Psi) = \sum_{k=0}^{\infty} (\rho_k^c \cos k\Psi + \rho_k^s \sin k\Psi) \quad (6)$$

Let us find the solution of equations (4) - (5) in a form

$$\tilde{U}(\tilde{r}, \Psi) = \sum_{k=0}^{\infty} (u_k^c(r) \cos k\Psi + u_k^s(r) \sin k\Psi) \quad (7)$$

Substituting (6) and (7) into (4) and put harmonic terms equal to each others the equations for $u_k^{c,s}(r)$ can be found

$$\frac{1}{\tilde{r}} \frac{d}{d\tilde{r}} \left(\tilde{r} \frac{du_k^{c,s}}{d\tilde{r}} \right) + \left(\frac{2\pi k R_a}{L} \right)^2 u_k^{c,s} = - \rho_k^{c,s}(\tilde{r}) \quad (8)$$

with initial conditions

$$du_k^{c,s}/dr(0) = 0, \quad u_k^{c,s}(1) = 0 \quad (9)$$

The beam flow radius R_b can be taken as constant as well as

each beam crossection can be taken as uniform. In our previous reports such beam was named as "frozen". Then in equation (4)

$$\tilde{\rho}(r, \Psi) = \begin{cases} (R_a/R_b)^2 & 0 \leq \tilde{r} \leq R_b/R_a \\ 0 & R_b/R_a < \tilde{r} < 1 \end{cases}$$

Below only bunching process without acceleration will be considered. In such case charge distribution remains symmetry with relative to the middle of period. All ρ_k^s and consequently all u_k^s are equal zero.

Solving equations (8) - (9) and taking into account that $\tilde{u}_k(R_b/R_a)$ and $d\tilde{u}_k/d\tilde{r}(R_b/R_a)$ must be continuous functions at the boundary of beam flow we have

$$U(\tilde{r}, \Psi) = - \sum \rho_k \left(\frac{1}{\omega k R_b} \right)^2 \left(1 - \frac{I_0(\omega k \tilde{r} R_a)}{I_0(\omega k R_a)} \cdot C(\omega k R_a, \omega k R_b) \right) \cos k \Psi$$

where $\omega = 2\pi/L$ and $C(x, y)$ is defined as

$$C(x, y) = \frac{I_1(y)K_0(x) + K_1(y)I_0(x)}{I_1(y)K_0(y) + K_1(y)I_0(y)} = y \cdot (I_1(y)K_0(x) + K_1(y)I_0(x))$$

Consequently $U(r, z) = \kappa \tilde{U}(\tilde{r}, \tilde{z})$ and

$$E_z = - \frac{\partial U}{\partial z} = \frac{2I}{\varepsilon_0 v L} \cdot \sum_{k=0}^{\infty} q_k F_k(\omega k r, \omega k R_a, \omega k R_b) \sin k \Psi$$

where q_k are harmonic coefficients in the expansion of $\frac{\partial}{\partial \Psi} \tilde{\rho}(\tilde{r}, \Psi)$

Let us consider fields at the axis of beam. With notations

$$x = \omega k R_a, \quad \gamma = R_b/R_a$$

we have

$$F_k(0, x, \gamma x) = F_{k0}(x, \gamma) = \frac{1}{(\gamma x)^2} \cdot \left(1 - \frac{C(x, \gamma x)}{I_0(x)} \right)$$

In this case

$$\lim_{x \rightarrow \infty} F_{k0}(x, \gamma) = \frac{1}{4} (1 - \ln \gamma^2) = D_0$$

and $F_{k0}(x, \gamma)$ is exponentially decrease with x growth.

The general view of $F_{k0}(x, \gamma)/D_0$ functions for γ from 0.1 to 1 with steps 0.1 are shown at Figs 1.1a and 1.1b. There are plotted 9 functions. The parameter γ is decreased from upper plot to lower one. As can be seen from Figs all functions are limited by the range from 0 to 1. For x tend to infinity (or k tend to infinity) they tend to 0 and for x tend to 0 (or L tend to infinity) they tend to 1. Fig.1.1b repeat the left part of Fig.1.1a in a large scale. Below $F_{k0}(x, \gamma)$ -functions will be called as harmonic factors.

1.2. "Frozen" beam bunching

Let us consider nonrelativistic axis proton bunching in a running wave with frequency ω and E_m as the first harmonic amplitude. The equations of motion have a form

$$m \frac{dV}{dt} = -eE_m \sin(kz - \omega t) + eE_c$$

where $\omega = \frac{2\pi c}{\lambda}$, $k = \frac{2\pi}{L}$, $L = \beta_c \lambda$, $\beta_c = v_c/c$, E_c is Coulomb field intensity.

Let us transfer from variable t to variable $v_s t = z_s$. In terms of this variable the above equations have the following form

$$m \frac{dV}{dz_s} = - \frac{eE_m}{v_s} \sin(k(z - z_s)) + eE_c$$

The second transfer to variable $\Psi = k(z - z_s)$ leads to the main equation of bunching

$$\frac{d^2\Psi}{dz_s^2} = - \frac{keE_m}{mv_s^2} \sin\Psi + \frac{keE_c(\Psi)}{mv_s^2}$$

with initial conditions for each particle

$$\Psi(0) = \Psi_0, \quad \frac{d\Psi}{dz_s} = \left(1 - \frac{v}{v_s}\right)k$$

Making the last transfer to "phase of bunching"

$$\tau = \Omega z_s, \quad \Omega^2 = \frac{keE_m}{mv_s^2}$$

and substituting the expression for Coulomb field intensity obtained in the previous part we obtain the main equation for bunching process analysis

$$\frac{d^2\Psi}{d\tau^2} = - \sin\Psi + \frac{2ID_0}{\epsilon_0 c \beta_s^2 \lambda E_m} \sum_{k=0}^{\infty} q_k \frac{F_{k0}(x, \gamma)}{D_0} \sin k\Psi \quad (10)$$

where q_k are harmonics of expansion $dq_k/d\tau$ in series in terms of Ψ , $x = 2\pi R_a/L$, $\gamma = R_b/R_a$, $D_0 = 1/4 \cdot (1 - \ln \gamma^2)$, $F_{k0}(x, \gamma)$ are the functions above determined.

The general view of equation (10) shows that in the context of given R_a/L and R_b/R_a the bunching process depends on the sole parameter

$$\alpha = 2ID_0/(\epsilon_0 c \beta_s^2 E_m \lambda) \quad (11)$$

It means that within the same geometric relations bunching process picture is the same until parameter $I/(WE_m \lambda)$ is keeping. Here W is particle energy. It is possible to find maximal alpha checking bunched beam quality. $\alpha_{\max}$ corresponds to beam current limit

$$I = \alpha W E_m / f \cdot \text{Const} \quad (12)$$

Comment 1.

Correlating the above equations and plots at Fig.1 the

conclusion can be made that current limit is increasing when R_a/L is risen because all Coulomb harmonics are decreasing. This conclusion is in error. In actuality the internal field intensity E_m is also decreasing proportional $1/I_0(2\pi R_a/L)$ and this effect leads to current limit decreasing.

Comment 2

There are no new terms in equation (10) for bunching process. It differs from common ones only by choice of unitless parameters. But our treatment differs in significant ways from popular opinion. It is common that ratio between phasing and Coulomb forces does not depend on beam energy and that Coulomb force is decreasing with energy growth owing to geometric factor R_a/L . In our new treatment energy growth leads to Coulomb parameter Alpha decreasing with inverse proportion although the first harmonic coefficients of Coulomb field are increasing with growth of L . As shown by Fig.1.1b the first harmonic coefficients are increasing only by factor 2 - 2.5 when L is infinitely increasing. The effect from α decreasing is over the effects from energy growth. If charge density is keeping bunch charge (and consequently beam current) is increasing with increase in wave length. Frequency decreasing leads to increase in phasing force and to increase in bunching process rate (process is finished after the smaller number of RF periods).

II

2. BEAM SIMULATION

Image-based package ZHALO was generated for space charge dominated beam bunching investigation. Its content, mathematical models and main tool parameters are described in *Appendix 1*.

2.1. Study of "Frozen" Beam Bunching.

2.1.1. Tasks and Methods.

As it was shown within the framework of considered model beam bunching dynamics depends on the sole parameter α provided that R_a/L and R_b/R_a are kept. The bunching process study reduces to this dependence understanding and cause and effect connection establishment.

Image-based code package ZHALO was used for research especially its part "Theory" (see *Appendix 1*). In the context of considered bunching model the equation is solved with initial conditions which are corresponding to mono energy beam with full RF period filling in:

$$\Psi(0) = \Psi_0, \quad -\pi \leq \Psi_0 \leq \pi, \quad \dot{\Psi}(0) = 0.$$

The equations (4) - (5) with uniform charge density inside the circle of radius R_b are solved at each step of integration. In an earlier work there was established that the best way for effective adiabatic bunching if RF field growth from small to nominal values at beginning part of accelerator. It is why the equation (10) is considered in a form

$$\frac{d^2\Psi}{d\tau^2} = -H(\tau)\sin\Psi + \alpha\tilde{E}_c(\Psi)$$

where

$$H(\tau) = E_0/E_m + (1 - E_0/E_m)(\tau/\tau_m)^2 \quad \text{for } \tau \leq \tau_m$$

$$H(\tau) = 1 \quad \text{for } \tau > \tau_m$$

coordinate τ_m and beginning level of field E_0/E_m are given.

There are the following view object:

- Coulomb field distribution (viewed at the background of external field sinusoid);
- beam charge distribution;
- particle kinetic energy distribution at the background of Coulomb field voltage distribution $U_k(z) = U(0) - U(z)$;
- beam longitudinal phase portrait at the background of external field separatrix;
- $S(z) = \sqrt{3\Psi^2}$ - phase length of equivalent bunch with uniform (over z) density and the same rms deviation;
- Coulomb field harmonic spectrum (the first five harmonics amplitude plots);

For R_a/L and R_b/R_a determination the beam with parameters typical for high-current CW linac was chosen: $f = 350$ MHz, $R_a = 3$ mm, beam energy $W = 0.1$ MeV, $R_b/R_a = 0.5$. (In the context of chosen parameters the value $\alpha = 1$ corresponds to current 0.4 A if $E_m = 1$ MV/m). When the investigation was made in the growth RF field $E_0/E_m = 0.2$ was taken.

2.1.2. Results Overview.

Visual observation of bunching process for SCD-beam shows the general tend as depend on α growth.

It is evident that particles with initial positions near the bunching center achieve this center at the earlier instant of time and form a Coulomb potential barrier for other particles. During the first quarter of phase oscillation period this barrier is increasing and each next particle meet its bigger opposition then the previous one. It means that during the first quarter of phase oscillation period a high-density core is formed inside bunch.

Starting from some alpha value the energy needed for particle to overcome the Coulomb barrier maybe comparable with kinetic energy which RF field has given to this particle. The typical points of inflection are appeared at phase portrait. For this alpha and for all bigger alpha values the beam can be named as SCD-beam.

On further alpha growth particle energy loss becomes more large as the center is approached. In its turn, phase oscillation amplitude can be increased owing to added momentum which a particle has assumed escaping from core. As will be shown below at this stage the proportion of particles which escape the phase period ($\text{abs}(\Psi) > \pi$) rise sharply. We call such particle as "loosed" ones.

The final stage of alpha growth leads to situation when particle full deceleration by core Coulomb field take place and particle cannot pass core. Nevertheless, as also be shown below beam bunching can take place in this case too. For this is needed to "match" the rate of Coulomb barrier growth with growth of particle kinetic energy. The "matching" can be made by choice E_0/E_m and z_m values.

Let us consider some specific examples. Phase portrait specific evolutions for SCD-beam are contained in report [5]. Here as an illustration we consider at the same picture particle kinetic energy points and plot of Coulomb potential energy.

During bunching process we can observe energy-phase trajectories of particle on the background deformed Coulomb potential energy distribution. Below evolutions of such "image" in different phase of oscillation period and for different alpha are presented. There are phase deviation from bunching center ($-\pi < \varphi < \pi$) as horizontal axis and unitless energy value as vertical axis. Value 1 for unitless energy corresponds to equality of kinetic and potential energies. White color corresponds to particle kinetic energy, green one to $U(0) - U(\varphi)$, i.e. particle energy needed to overcome the Coulomb potential barrier, red color is used for kinetic energy of "loosed" particle. For comparison at Fig.2.1 the same figures are presented for zero current ($\alpha = 0$).

Case A. Beam Bunching in RF Field with Constant Amplitude

$$(H(t) = 1)$$

In this case phase portrait deformations are started from $\alpha = 0.15$, kinetic energy is comparable with potential for alpha near to 0.3 and proportion of "loosed" particles rises sharply from $\alpha \geq 0.5$.

At Fig.2.2-2.4 the evolution of energy features for α equals 0.15, 0.3 and 0.6 correspondingly are presented. It can be seen that for $\alpha = 0.3$ particles stored in bunching center is essential to change of particle energy in spite of the fact that particle kinetic energy far greater than Coulomb potential energy. For $\alpha = 0.3$ kinetic and potential energies are comparable. The particles which pass the core in the moment when core has its highest density take added momentum from the core. This momentum rises amplitudes of particle oscillations. The situation is in perfect analogy to transverse oscillations of SCD-beam described in report [5]. In this work a halo formation mechanism was studied. Kinetic energy is added for particle which passes the core in the stage when core density is increasing. For $\alpha = 0.6$ potential energy is comparable with kinetic one and "halo" oscillation growth is an added source of particle "losses".

It is evident that there are two sources for particle losses caused by longitudinal motion. The first one is vertical narrowing of stability oscillation zone. As a result of this factor boundary particles come out from this zone. When RF amplitude is constant this effect is present also in the case of small alpha although proportion of loosed particles is small. The second loss source is amplification of longitudinal oscillation for particles which pass the core in the stage of core density compaction. By analogy this effect can be named "halo formation". With alpha increasing halo oscillations are amplified and beginning with some alpha value (in considered case with $\alpha = 0.5$) amplitude of halo particle oscillation exceeds π .

The equation $\varphi_{\text{halo}}(\alpha) \leq \pi$ can be taken for determination of

upper α limit. In considered case SCD-beam bunching and acceleration are possible only for $\alpha \leq 0.5$. It is evident that for practical purposes 2 - 3 times smaller value must be used.

SCD-beam bunching study in the case when constant RF amplitude is used shows that high bunching quality can be achieved conceptually.

Case B. Beam Bunching in a Channel with RF Amplitude Build-Up

$$H(z) = E_0/E_m + (1 - E_0/E_m) \cdot (z/z_m)^2 \quad \text{for } \tau \leq \tau_m$$

$$H(\tau) = 1 \quad \text{for } \tau > \tau_m$$

Previous Case A analysis gives an indication how constant RF amplitude leads to beam-channel mismatching during bunching process. A channel with with RF Amplitude Build-Up is needed for beam matching and high current realization. The main goal is to optimize build-up form. Based on previous study of work and on many calculated versions it can be stated that build-up plot in the form of parabola

$$H(z) = E_0/E_m + (1 - E_0/E_m) \cdot (z/z_m)^2,$$

where $E_0/E_m = 0.2$ and z_m contains 1 - 1.5 periods of longitudinal oscillations (Note: Below we use maximal E_m for alpha determination.)

Because the external RF field in the begin of channel is small Coulomb effects has become detectable for smaller α . At Fig.2.5 the evolution of energy characteristics are presented for $\alpha = 0.07$ where Coulomb effects can be seen. Visual analysis shows that in the case of RF amplitude build-up (Case B) the core essential influence is started from a more smaller kinetic energy of particles then in Case A. In Case B total core charge is smaller. For the same alpha the added momentum from core is small and it can not rise amplitude of particle oscillation by a large margin. Although the Coulomb potential energy exceeds particle kinetic energies bunching process practically without losses takes place up to $\alpha = 1.2$. It means that limit current is doubled. The increasing of z_m from 1 to 1.5 increase α limit from 1.2 to 1.4 but no more. At Figs.2.6 and 2.7 the evolution

of energy characteristics are presented for $\alpha = 0.6$ and 1 ($E_0/E_m = 0.2$, $z_m = 1$). The absence of particles between two green plots have engaged our attention. Particles can not pass the core but attraction momentum does not escape them from stability zone of bunching. At Fig.2.8 plots of equivalent phase length and of Coulomb field harmonics are indicated for $\alpha = 1$ at the length of 8 phase oscillation periods. It can be seen particle stability motion for $\alpha = 1$.

The comparison between constant and build-up RF field gives a possibility to state that in Case B beam phase rms length is essentially smaller. This statement is valid for zero current too. This conclusion is confirmed by Figs 2.9 and 2.10 where plots of equivalent phase length for constant and build-up RF field are indicated for $\alpha = 0$ and $\alpha = 0.5$.

A second trend has emerged from the observation of Coulomb field harmonic spectrum for "frozen" beam. With increasing in alpha the first harmonic of Coulomb field far exceeds the others. Its amplitude approximates the external field one. At Fig.2.11 harmonic spectrum for $\alpha = 0.3$, $\alpha = 0.6$ и $\alpha = 1.2$ are shown. It can be said that SCD-beam automatically makes Coulomb field distribution similar to external field one. Such high-current effect can be considered as a beam "automatching" with a channel. Along with it for small alpha higher harmonics are comparable with the first one and can cause local resonance effects in beam transverse motion.

Case C. Consideration of Coulomb and RF Field Transverse Nonuniformity

Previous analysis is based on particles which are moving along longitudinal axis. The charge distribution is generated also by axis particles. In reality particle execute transverse motion. With regarding to increase of r Coulomb field intensity $E_{col}(r,z)$ is decreasing but RF field intensity $E_{ext}(r,z)$ is increasing. Bunching forces are larger for peripheral particles than for axis particles.

The corrections in the considered effects must be applied when longitudinal oscillation frequency depends on radius. It is

not so easy to predict final result. On the one hand the Coulomb effects are decreasing because the relation between Coulomb and bunching fields is changed in favor of bunching one. On the other hand transverse nonuniformity leads to:

- a) transverse velocity increasing for peripheral particles,
- b) core density increasing due to a),
- c) core counteraction increasing for particles near axis.

Model for bunching process used in ZHALO.THEORY does not take into account particle transverse motion. But it can be considered the transverse motion of "radial layers" with the same and constant radius for all particle inside layer. Such model can not give the quantity description of transverse motion but can quality estimate longitudinal oscillation effects owing transverse nonuniformity.

Investigations with the use of ZHALO.THEORY show that all physical relations and effects brought out for particles near axis are valid in general case too. There is small quantitative difference between results in both cases. For the same alpha loosed particle number is larger in the "layer case" then in the "axis case". The last fact indicates that the effects from faster charge accumulation inside core by peripheral particles are stronger then effects from average phasing force increasing relative to Coulomb one.

III

3. SCD-BEAM SIMULATION IN SSF CHANNEL.

Let us going now to results of SCD-beam calculations obtained by using ZHALO.Trans+Long. Simulation of beam with azimuthal symmetry in a drift tube channel with focusing by superconducting solenoids is carried out with help of these codes. Coulomb field is determined by solving Poisson equation in cylindrical domain with $\beta\lambda$ as its length and R_a as radius. Charge distribution is generated by macroparticles having ring form.

Two goals were pursued by beam simulation. The first goal is to compare results obtained by simulation with ones predicted by theory. The second goal is to choose optimal parameters for the beginning part of deuteron 40 MeV linac.

3.1. The Applicability of Previous Analysis Results

"Frozen" beam model differs from "real" beam model in two aspects: no account has been taken in "frozen" beam calculations of beam density radial nonuniformity and of beam kinetic energy radial-longitudinal redistribution. In order to compare these two models beam bunching simulation was made for case with following parameters:

Beam current	250 mA
Beam emittance	0 cm ² ·mpad
Bore radius	3 mm
Beam radius	1.5 mm
E_m	1.2 MV/m
E_{m0}/E_m	0.2
$z_m/\beta\lambda$	30
RF cell number	100
Operating frequency	352 MHz
Focusing field	4.5 T

Input beam was presented as uniform charged cylinder without initial energy spread. Total channel length corresponds to 4.5 periods of longitudinal zero-current oscillations, channel part up to z_m corresponds to 1.35 periods.

The comparison in results shows that "frozen" and "real" beam having the identical behavior: practically in the time the high-density core is generated, particles are oscillated with the same frequency and they in the same manner are attracted from core. Maximal value of generated transverse kinetic energy is one tenth from kinetic energy of longitudinal oscillations. The conclusion about good agreement for SCD-beam can be made.

Along with it calculations show that bunching process is accompanied by growth of transverse oscillation amplitudes for particles from central beam part after 1/4 of longitudinal oscillation period. Beam phase portraits at the stage of core formation are indicated on Fig.3.1.

3.2. Beam Transverse Matching on the Stage of Bunching (By the Example of Deuteron Linac Beginning Part)

3.2.1. Theoretical Approach

Let us return to equation for $U(r, z)$ obtained in previous part for beam with periodical distribution over z and uniform distribution in each crosssection. The equation for $E_r(r, z)$ can be obtained from it

$$E_r(r, z) = \frac{I}{\pi \beta c R_b^2} \sum_{k=0}^{\infty} \rho_k \frac{I_1(\omega_k r)}{\omega_k I_0(\omega_k R_a)} C(\omega_k R_a, \omega_k R_b) \cdot \cos(\omega_k z) \quad (13)$$

The harmonic coefficients

$$G(x, \gamma x) = \frac{1}{I_0(x)} C(x, \gamma x)$$

for $\gamma = 0.1 - 1$. with step 0.1 are presented on Fig.3.2. The top plot corresponds to minimal value of γ , the bottom one - to maximal value of γ .

It can be seen from equation (13) and indicated plots that for small $x = 2\pi R_a/L$ the transverse component of Coulomb force $E_r(r,z)$ faithfully copies the charge distribution and for small γ is coincident with it in wide x interval.

The formal linearization gives

$$E_r(r,z) = \frac{I}{2\pi\beta c R_b^2} r \sum_{k=0}^{\infty} \rho_k \cdot G(\omega_k R_a, \omega_k R_b) \cos(\omega_k z) \quad (14)$$

(the linearization is possible because harmonic coefficients exponentially decreasing when harmonic number is increasing (x tends to infinity)).

On Fig.3.3 the transverse Coulomb force at the background of charge distribution is indicated for $x = 1.5$ (such value is specific for linac beginning part), bunch phase length 180 deg., and for R_b/R_a equals 0.15, 0.5, 0.95. It can be seen that for $R_b/R_a = 0.5$ Coulomb force increasing is smaller then beam density increasing. It is seen also that for uniform charge density distribution inside bunch transverse component of field intensity $E_r(r,z)$ is nonuniform over z . This leads to effects described in report [5] and will end up as a source of halo formation: Coulomb field essentially differs for particles which pass the same crosssection point in different instant of time.

It is significant that a growth of harmonic coefficients with decreasing of r owing to mismatching beam contraction also can be a source of halo increasing.

3.2.2. SCD-beam Simulation and Calculation in the Beginning Linac Part.

The following parameter can be chosen as specific for the linac beginning part:

Beam Current	100-250 mA
Input Energy	100 keV/nucleon

Operating Frequency	350 MHz
RF Amplitude	1.2 MV/m
Beam Radius/Aperture Bore	0.5

For such parameter choice

$$0.2 < \alpha < 0.7$$

SCD-beam dynamics was considered in the beginning part of linac with focusing by longitudinal magnetic field. Input beam had an uniform distribution with given emittance value. Beam radius growth was observed if input beam was matched as usually. The growth is a result of beam density increasing on account of bunching. For beam current 250 mA transverse oscillation amplitude increases by factor 2 and particle losses appear. The optimal choice of focusing field together with transverse size and input beam envelope tilt must receive sufficient attention.

The manner of equivalent bunch length establishment suggests that this value must be taken into account for beam matching with focusing channel. Transition to a steady state can be optimized by input beam transverse parameter choice.

At Fig.3.4, 3.5 beam phase and transverse trajectories are indicated for the beginning part of proton linac with following parameters:

- operating frequency	175 MHz
- accelerating field mean amplitude	1.2 MV/m
- bore radius	6 mm
- input energy	0.1 MeV
- output energy	2 MeV
- beam current	250 mA
- beam emittance	$0 \pi \text{ cm} \cdot \text{mrad}$
- input beam radius	2 mm
- beam input divergence	10 mrad
- focusing field	4.5 T

There are 217 accelerating periods with $\beta\lambda/2$ as each period length. Cavity total length is 5.14 m. Fig.3.6, 3.7 corresponds to the same channel and beam parameters but with emittance $0.1 \pi \text{ cm} \cdot \text{mrad}$. In this case halo size does not exceed bore

radius.

Remark. A possibility to match bunching beam by focusing field build-up at the beginning part of linac is outside of this work. It must be noted that such optimization depends on particular beam parameters. The magnetic field build-up form cannot be changed when input beam parameters are varied.

MAIN STATEMENTS

1. For given geometric relations R_a/L and R_b/R_a beam bunching process for SCD-beam depends on the sole parameter

$$\alpha = \frac{2ID_0}{\epsilon_0 c \beta^2 \lambda E_m}$$

Number n of phase oscillation periods is used as measure for bunching process duration T

$$T = n/\omega,$$

where ω is phase oscillation frequency and

$$\omega^2 = \frac{eE_m k}{mv^2}, \quad k = 2\pi/\beta\lambda$$

Bunching beam parameters are keeping if with beam current increasing in the same proportion as operating frequency is decreased or as particle energy is increased.

Beam bunching process in RF field with amplitude build-up is kept its SCD features when $\alpha > 0.7$. When $\alpha > 1.2$ particle losses take place and beam bunching without losses is impossible in principle. If $f = 350$ MHz, $W = 0.1$ MeV, $E_m = 1.2$ MV/m, then $\alpha = 0.7$ corresponds current 30 mA and $\alpha = 1.2$ corresponds current 500 mA).

Beam current limit is determined by E_m if f and W are given. For RFQ linac intervane voltage is equal 100 kV

($f = 350$ MHz) and for acceleration efficiency in bunching part $\kappa = 0.03-0.05$ gives estimate $E_m < 0.3-0.5$. For SSF linac $E_m < 3$ MeV/m and beam current limit is 5-10 times the RFQ current limit.

2. In order to bunch effectively SCD-beam a linac beginning part with amplitude build-up and with length about 1 - 1.5 T is necessary in concept.

3. Coulomb field harmonic spectrum is determines by the first harmonic which essentially exceeded all others as beam current is increased ($\alpha > 0.8$).

4. Bunch equivalent length (bunch longitudinal rms size) is established fast during bunching process.

5. Focusing field magnitude must be chosen reasoning from bunch equivalent established length. Transverse dynamics optimization may be made by input beam parameter choice.

APPENDIX 1

Brief Image Based Codes ZHALO Overview

Image Based Codes package ZHALO was generated with special purpose to perform the above work. It is designed for physical understanding of SCD-beam bunching and accelerating processes in the beginning part of ion linac. Codes give a possibility for visual observations of beam portraits and distributions on phase space during bunching and initial acceleration. There are two package parts: ZHALO.Trans+Long and ZHALO.Theory.

1. ZHALO.Trans+Long.

This part of codes are designed for study core-halo formation in the stage of bunching and initial acceleration in RF structure. Beam transverse focusing is performed by longitudinal magnetic field (SSF HILBILAC).

1.1. Mathematical Model.

The accelerating channel consists in the drift tube structure with drift tube and gap length defined from RF amplitude and synchronous phase plots given by user as function of accelerating period number. Transverse focusing is carried out by superconducting solenoids. Beam is defined as set of macroparticles uniform distributed inside round cylinder with given radius and phase width. Phase width in 360 degrees corresponds to unbunched beam. Particles have longitudinal and transverse velocities based on given spread of energies and input emittance magnitude. Particles experience an action from RF electric field (E_z and E_r), from RF magnetic field (H_ϕ), from external magnetic field of solenoids (B_z and B_r) as well as from the same components of Coulomb electric field. For Coulomb field calculation the Poisson equation was solved at each step of integration with periodical boundary conditions:

$$U(r,0) = U(r,L), \quad dU/dr(0,z) = 0, \quad U(R_a,z) = 0$$

Macroparticles are defined as rings with the same transverse area and the same extent over z-axis.

1.2. Visual Information.

On line with process calculations the following information is displayed on different windows:

- beam phase portraits $(Z-Z_s, W_z - W_{zs})$ on the background of channel separatrix, (r, W_r) , (z, r^2) and (W_z, r) all on the background of bore radius, (z, W_r) and (W_z, W_r) , where W_z and W_r are kinetic energies of longitudinal and transverse motions;
- distributions of Coulomb voltage and Coulomb intensity E_z over z for $r = 0$ and for $r = R_b$ which is an equivalent radius of uniform charged beam;
- charge distribution over z for $r = 0$ and $r = R_b$;
- distribution of Coulomb E_r intensity over a middle crosssection and over two crosssections between which a preset (by user) charge proportion is included;
- transverse charge distribution inside the channel (several colors are used for beam density different levels);
- trajectories of particle phase motion;
- trajectories of particle radial motion;
- trajectories of core envelopes for above crosssections.

Together with visual information user has information about current values of accelerating period length, mean energy, beam current and beam proportion escaping from bore radius and from accelerating mode.

2. ZHALO.Theory.

This part of codes are designed for understanding the main features of SCD-beam adiabatic bunching. They are based on equations derived in previous analytical part of Report. Only main Coulomb effects of longitudinal motion are considered in models realized in this part.

2.1. Mathematical Model.

The longitudinal motion is considered in the field of equivalent running wave and in beam own Coulomb field. Particles do not execute a transverse motion and move inside a cylinder of constant radius. Motion of particles are described by equation

$$\frac{d^2\Psi}{d\tau^2} = -H(\tau) \sin\Psi + \alpha E_c(\Psi),$$

$$H(\tau) = E_0/E_m + (1 - E_0/E_m)(\tau/\tau_m)^2 \quad \text{for } \tau \leq \tau_m$$
$$H(\tau) = 1 \quad \text{for } \tau > \tau_m$$

The following task is solved for Coulomb field calculation

$$\frac{\partial^2 U}{\partial \Psi^2} \left(\frac{2\pi R_a}{L} \right)^2 + \frac{1}{r} \left(r \frac{\partial U}{\partial r} \right) = -\rho(r, \Psi)$$

$$\partial U / \partial r(0, \Psi) = 0, \quad U(r, 0) = U(r, 2\pi), \quad U(1, \Psi) = 0$$

$$\rho(r, \Psi) = \begin{cases} (R_a/R_b)^2 & 0 \leq r \leq R_b/R_a \\ 0 & R_b/R_a < r < 1 \end{cases}$$

Coulomb parameter α may vary within limits given by user. For calculation of charge distribution particles are defined as uniform charged disks with the same extent over z .

2.2. Visual Information.

During process of bunching a user can visually observe the evolution of:

- Coulomb field distribution on the background of external field sinusoide;
- beam charge distribution;
- particle kinetic energies on the background of potential barrier generated by core particles;
- beam phase portrait ($Z-Z_s, W-W_s$);
- plot of beam equivalent phase width;
- the first five Coulomb field harmonics.

User has also information about current values of α , passed part of oscillations, loosed particle fraction.

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IV

20 MeV/N 250 mA DEUTRON LINEAR ACCELERATOR

4.1. Principal scheme of accelerator

The principal scheme of deuteron CW linear accelerator are shown in Fig.4.1-1. Accelerating system consists of 14 accelerating resonators (AR) excited at H_{111} wave. Along with HILBILAC case described in work [4.1], accelerating structure with opposite vibrators loaded by drift tubes at the ends is used in this case. Operating frequency was chosen rather low and equals 175 MHz; this is because it is necessary to have feasible dimensions of the first part of AR. As calculations indicate accelerating structure can effectively operate along the accelerator from 0.15 to 40 MeV. Average accelerating rate is chosen as great as 1 MeV.

Focusing system bases on superconducting solenoids that cover accelerating resonator (see 4.6). The first two resonators are placed inside single long solenoid 7.5 m in length; RF power feed is accomplished through the faces of AR. Next twelve AR are placed inside the system of periodically arranged solenoids of lesser length.

RF supply system bases on the classical scheme (see 4.4): each AR is excited by its RF channel based on CW klystron amplifier with 1.8 MW power.

The main parameters of accelerator are shown in the Table 4.1.

Table 4.1

Main Parameters of 40 MeV 250 mA CW deuteron linear accelerator with superconducting solenoids (SS)

Resonator type	H-resonators with opposed vibrators
Injection energy	0.15 MeV
Output energy	40 MeV

Current	250 mA
Momentum spread	1.2 %
Beam effective emittance (normalized)	0.35π cm·mrad
Accelerating field frequency	175 MHz
Accelerating rate	1 MeV/m
Number of resonator	14
Resonator length	4...1 m
Resonator diameter	400 mm
Equilibrium phase	90...30 degr
Focusing type	SS
Magnetic field inductance	6.5...5 T
Acceptance (normalized)	1.4π cm·mrad
Number of solenoids	7
Solenoid length	7.5...1.5
Diameter of "warm" field of solenoid	0.6 m
Number of klystron generators	14
Klystron generator power	1.3 MW
Total RF power	14 MW

Feasibility study and characteristics of accelerator main systems chosen on the base of calculations and beam dynamics requirements are presented in following chapters. Accelerator design characteristic properties associated with communications to AR placed inside superconducting solenoids are discussed as well.

4.2. Accelerating structure

It is reasonable to use accelerating structure based on excitation of the wave with longitudinal magnetic field in cylindrical resonator (so called H-resonator) as the structure for deuteron acceleration (starting from 0.15 MeV). H-resonators are in practical implementation and have high efficiency typically for low relative velocities of particles ($\beta = 0.005-1$). As in the case of initial part of CW proton linear accelerator, reported in [1.1], structure with opposed

vibrators loaded at the end by drift tubes and exited at H_{111} wave was chosen as accelerating structure (see Fig.4.3-1). Structure prototype was developed for heavy ions accelerator [4.2]. This type structure choice criterions were standard requirements: construction simplicity, relatively small transverse dimensions, high shunt efficiency. In addition, in deciding on AR type allowance was made for AR construction have to provide good heat removal and have to be test in operating accelerator.

Operating frequency was chosen relatively low and equals 175 MHz; the reason is that it is necessary to provide practically reasonable dimensions of initial structure cells. As may be seen from preliminary calculations, it is possible to use this structure up to the energy of 40 MeV, that is to the end of accelerator.

Fashion of the tuning of heterogeneous structure cells is the possibility of changing of the angle between neighboring vibrators from 180° at the last, the most longer cells, up to the value that provides demanded field distribution along AR.

Accelerating system will consist of 14 resonators. Distances between resonators are equal to $\beta\lambda$ (where β is particle relative velocity, λ is operating wavelength). In practice resonators will be separated only by partition. Length of some initial cells (period) of structure is $3/2\beta\lambda$, that is generally concerned with real longitudinal dimensions of drift tubes (with respect to manufacture and heat removal). The following cells will be $\beta\lambda/2$ in length.

The following resonator design is proposed.

Cylindrical resonator 400 mm in diameter contains drift tubes; drift tubes axis aligns with resonator axis. Aperture opening is 10 mm in diameter; external diameter of drift tubes is 20 mm. All odd tubes are connected with the plate 10 mm thick; plate is fixed along resonator generatrix, its length is equal to the distance between outer edges of drift tubes. Tubes are connected with the plate by radial bars 6...10 mm in diameter. The distance between structure axis and plate is equal to 60 mm. Channels for cooling water circulation were allowed in

the plate. Even tubes each are connected with resonator by sector; sector angle is altered (at the initial part of the structure it is about 180°). It is essential difference from prototype. Channels for cooling water flowing are allowed in these sectors. Outer even semi-tubes are placed on the face covers of resonator.

Second dissimilarity from prototype is connected with the absence of focusing elements inside all drift tubes; this fact not only allows to decrease external diameters of drift tubes, but allows to reduce requirements imposed on accuracy of manufacturing, alignment and position stability in time as well.

The same constructive elements as in the case of first version of proton linac [4.1] are used for frequency tuning and forming of demanded distribution of accelerating field in the structure.

According to estimation the value of shunt impedance is varied over a range from 200...250 MOhm/m to 40 MOhm/m, except for the initial periods, that are $3/2\beta\lambda$ in length, where shunt impedance will be considerably lesser. The main part of RF losses will release in plate, bars and sectors (estimated value is up to 90%).

During development of specific resonator design the code package ISFIELD3D will be used; it was used for development of accelerating system concept as well. This package is dedicated to calculation of electro-magnetic field and parameters of RF apparatuses with an arbitrary form of ideally-conducting surfaces by means of solving of vector 3D electrodynamic task. Electromagnetic field components, local and integer performances and parameters of devices at demanded frequencies are the solutions of this task.

Codes are write in FORTRAN 77 language and realized as four separated processors (modules), taking into account functional features of different stages of task solving: geometrical modeling processor, discretization, calculation and post-processor. Data flow communications from one module to other one are accomplished by interface information accumulator.

Personal computer AT486 with clock rate of 66 MHz and

NDP386 FORTRAN will be used for calculation.

According to preliminary investigations with the help of this code it is possible to calculate structure by separated compartment (bounding planes along z axis go through middles of neighboring drift tubes), with conditions on bounding plates according magnetic wall conditions ($E_n = 0$, $H_t = 0$). Validity verifications of two bars changing for attachment of odd drift tubes (as in prototype) by sector were gained.

Power input into each resonators will be accomplished with the help of coupling loop as viewed from face walls (loop is placed in plane going through middle of drift tubes).

Parameters of first and end resonators of initial part are listed in Table 4.2.

Table 4.2

N resonator	1	14
Resonator diameter, mm	400	400
Resonator length, m	4	1
Aperture diameter, mm	10	10
Drift tube diameter, mm	20	20
Nominal value of RF power dissipated in copper, kW	0.01	0.06
RF power per beam acceleration, MW	0.04	0.75

2.3. RF Supply System of Deuteron Accelerator

Accelerator RF system (its block-scheme is presented in Fig.4.1-1) consists of 14 RF amplification channels (AC) operating on a frequency of 175 MHz, feeder system (FS), powerful mastering device (PMD) (its frequency is stabilized by quartz) and line of excitation and reference phase EL-1.

For unification all channels are made for the same determined RF power of 1300 MW. This RF power is used for compensation of RF losses in elements and devices of feeder

system. In addition, RF power reserve of 15-20% is provided for operation of system of RF field level automatic control. It is suggested to use klystrons as output devices. Klystron with output energy of 1000 kW at frequency of 200 MHz developed in MRTI in collaboration with SSIU "TORIY" and modified klystron YK-1350 with output energy of 1300 kW at operating frequency of 350 MHz (it is used in RF system of LEP-2 complex [4.3]) may use as prototypes of such device.

Klystron proposed parameters at frequency of 175 MHz are as follows:

- operating voltage	100 kV
- beam current	2.5 A
- DC to RF conversion efficiency	65%
- current of modulating anode	< 5 A
- maximal load SWC	1.2

RF power from klystron output is fed to resonator through coaxial feeder with water cooling. It is $300 \times 130 \text{ mm}^2$ in cross-section. At the section near resonator coaxial feeder cross-section is decrease to $115 \times 50 \text{ mm}^2$. RF window is placed at this section outside magnetic screen enveloping superconducting solenoids of beam focusing. Energy output window of klystron YK-1350 may be used as prototype of seal window design.

Ferrite circulator is applied into coaxial feeder between resonator and klystron output for stable operation without generation of unwanted oscillations when load profoundly altering. Circulator parameters are as follows: output-to-input-port isolation (S_{12}) > 20 db, losses in the forward direction < 0.1 db and input reflection > 20 db.

Systems of automatic control of RF field amplitude and phase (see Fig.4.4-1), as well as system of automatic control of resonator frequency are traditional ones for ion linear accelerator [4.4].

In the system of RF field amplitude stabilization RF signal detected in amplitude transducer (AT) is compared with specified standard (reference) voltage E_r . In the section of control in response to signal of error (SC) of amplitude automatic control system control signal is generated for control of klystron RF

output power. Control of klystron RF output power is accomplished by changing of RF excitation voltage or by changing of voltage of klystron modulating electrode.

Control of RF field phase in resonator is accomplished by signal of error generated in phase transducer (PT) by way of comparison of phase of RF voltage from resonator with the phase of RF voltage from reference line of EL. Control of RF voltage phase at the output klystron cascade of excitation is accomplished by signal of error in SC of phase automatic control system (PAC).

In the system of automatic control of resonator frequency tuning RF signals from resonators and from RF field transducer in coaxial feeder are compared in phase detector (PD). Signal of error is fed into SC PAC, which control by final-control of PAC.

2.4. Focusing system

Focusing system of accelerator is presented in Fig.4.6-1. Demanded field distribution is achieved with the help of seven solenoids from 7.5 m to 1.5 m in length. There are technological gaps between solenoids for RF power input into resonator. Maximal induction of magnetic field on solenoid axis is from 6.5 T to 5 T. Each solenoid envelops two resonators.

For superconducting solenoids with magnetic field inductance up to 10 T it is the most promising to use NbTi alloy twisted in copper matrix as superconducting material. Superconducting alloy stabilization in matrix is achieved by connection superconductor with the metal having high conductivity under condition of good contact with coolant.

Analysis of the magnetic field and temperature dependence of critical current density shows that for magnetic field inductance of $B = 5 \text{ T}$ at temperature of $T = 4.2 \text{ K}$ critical current density in superconducting alloy NbTi placed into copper matrix is 1200 A/mm^2 , and for $B = 6.5 \text{ T}$ - 900 A/mm^2 . So it is possible to use standard superconductor produced by Russia industry for solenoid reeling up. In this superconductor the

amount of stabilizing copper is about 50%. Chosen superconductor parameters estimation shows that critical current for $B = 5$ T is equal to 3400 A and for $B = 6.5$ T is 2800 A; specified conductivity of composite conductor is of the order of 10^{-12} Ohm·cm. Consequently, it is possible to choose limiting current in solenoids as large as 2000 A. It is possible to define solenoid losses from volt-ampere characteristic of stabilized composite conductor with permanent current. In the case being considered losses are about 2 W for $B = 5$ T and are 24 W for $B = 6.5$ T.

For solenoid stable operation in permanent current accelerator complex the following stability criteria have to be ensured:

- criostatic stability connected with reserve current flow with high conductivity for the case conductor transition into normal state;
- enthalpy stability connected with decrease of adiabatic abrupt change of flow during superconductor transition into normal state through introduction of material with adequate heat;
- dynamical stability connected with damping of abrupt change of magnetic flow, that prevents growth of possible instabilities.

Appropriate choice of fibers thickness of superconductor and amount of stabilizing material make it possible to construct stabilized solenoids; degradation effect is essentially decreased and sufficiently slow growth of voltage on the clamps during superconductor transition into normal state is provided in its. It makes possible to use protection effectively and optimally use internal stabilization with limiting current densities.

Initial data for calculations of superconducting solenoid design are as follows: specified value of magnetic field, its distribution along axis and resonator geometry. The main criteria of solenoids calculations was its minimal volume with given magnetic field on accelerator axis. For calculations of focusing fields generated by solenoid system the method of

spherical expansion of field was used; it made possible to determine the dependence of on-axis field on the number of wraps in each solenoid sections and to determined inhomogeneity factor.

According to estimation in this case it is appropriate to use four-order solenoid with higher current density at the ends. It allows to remove field "crevasse" on axis between neighboring solenoids.

Characteristics of minimal volume solenoids with optimal energy consumptions are listed in Table 4.3.

Table 4.3

**Main Parameters of Solenoids
Used for Magnetic Field Generation in Accelerator**

Parameter\Number of Solenoid	1	2
Solenoid Current, A	2000	2000
Magnetic field induction, T	6.5	5
Specific Number of wraps in central part, 1/cm	26	20
Diameter of warm solenoid-field, m	0.6	0.6
Outer diameter, m	0.72	0.68
Solenoid length, m	7.5	1.5
Section of matrix with 50%-filling, mm ²	2×3.5	2×3.5
Superconductor material alloy	Nb-Ti	Nb-Ti
Matrix material	Cu	Cu
Maximal filling factor	0.8	0.5
Constructive current density, A/mm ²	150	150
Number of blocks 0.5 m in length	15	3
Inductance, H	23	2.7
Storage energy, MJ	46	5.4
Energy storage in block, MJ	3.1	1.6
Heat losses, W	24	2

For facilitation of assembling and construction it is necessary to assemble solenoid of block 0.5 m in length. In this

case mechanical assembling of magnetic system become more conveniently and it is possible to use effective methods of solenoid protection during its transition into normal state.

The main heat flows into criostat from environment are heat radiation and flow in current inputs and solenoid supports. According to calculations heat flow into criostat without additional screen through heat radiation is 3000-600 W, that is unsuitable. For decrease of load on cryogenic system and for saving of energy consuming by refrigerator it is necessary to use the whole complex of methods used in modern design of superconducting magnetic system. In this case crio-system has to consist of the following elements:

- vacuum envelop,
- 15-ply super-isolation,
- nitrogen screen ($t = 80 \text{ K}$),
- vacuum envelope,
- gaseous helium screen ($T = 9 \text{ K}$),
- 5-ply super-isolation,
- vacuum envelop,
- helium volume at temperature of 4.2 K with superconducting solenoid inside.

Vacuum envelope is the main load-bearing element of criostat. Next vacuum envelopes support the forces from magnet through dielectric chain suspension and telescopic supports to outer vacuum envelope. Such scheme of force suspension of magnetic system makes it possible to significantly decrease heat flow into criostat not only through radiation but through supports as well.

Current inputs with heat flow up to 2 W per 1000 A for couple of inputs are used in modern powerful superconducting magnets.

The presence of support elements in construction of solenoids and criostats provides stiffness of solenoid and crio-system as a whole but introduces additional heat flow. Design and dimensions of supports are determined by unbalance forces connected with magnetic interaction between individual coils as well as its position relative to ferrous envelope of

magnet. In addition, errors of coils alignment in relation to ferrous yoke leads to increase of transverse section of supports and accordingly to increase of heat flow. In design of modern magnetic systems for solenoids of 400 kg in weight it is possible to decrease heat flow through supports as small as 10-12 W and for solenoids 2000 kg in weight as small as 70-80 W.

According to estimation total heat ingress into criostats will not higher than 100 W.

From the point of view of mechanical stability the main problem is axis ponderomotive forces acting on neighboring magnets, which attract each other with force as higher as 10 t. Mutual displacement of solenoid leads to dangerous heat release. As this take place, it possible such negative effects as degradation an training of superconductor. So at the stage of design investigations it is necessary to concentrate our attention on system of solenoid connection with criostat and connection of criostat between each other with demanded stiffness. So the problem of ponderomotive forces is extended to force elements of construction such as supports and suspensions. Ponderomotive forces act on individual wraps of solenoids as well; so it is necessary to make its monolith in block with the help of thermosetting materials.

For providing of criostat stiffness relative to each other they must have common base; common magnetic screen can serve as this base. Magnetic field energy stored in long solenoid amount to as much as 46-5.42 Mj; so there is a problem of magnetic screen protection during transition from superconducting to normal state. Strong mutual induction between neighboring coils just makes decision of this problem more difficult.

Solenoid protection from destruction during transition to normal state have to provide both by internal criostat elements and by energy dissipation outside of criostat.

For solenoid protection during transition to normal state it is necessary to place each solenoid block on copperwork; such framework is favorable to uniform winding heating. In addition, solenoid winding have to be shunt by special heaters placed inside solenoid; they heat up whole winding of solenoid block

with action of normal state detector and transform solenoid into normal state, that decrease possibility of its destruction.

For solenoid protection during transition to normal state ones have to use such scheme decision as schemes on the base of varying shunt resistance with small resistance and diodes; they make possible to achieve dissipation of 90% of field energy outside of criostat.

During operation of powerful superconducting magnetic system, the following time factors of transition to normal state are defined:

- normal state expand along conductor with the speed of 10-20 m/c;
- time factor of normal state expansion in solenoid is 0.001-0.1 c;
- time factor of transformation of magnetic energy to heat in solenoid is 0.7-1.5 c;
- time factor of heat expansion from coil to helium tank is 10-20 c.

Time factors make possible to design solenoid protection system based on rational combination of described methods.

Because of set of reasons long extent of focusing system and strong inductive solenoid coupling make difficult termination of avalanche during transition of one solenoid to normal state. Use of traditional methods of termination in this case is not sufficient. Effective method of control against "electromagnetic avalanche" in this case may be introduction of pulse compensating solenoid placed in the immediate vicinity of the gap between solenoids and applied on main solenoids or in the gap between its.

In mode of "failure" or magnetic field abrupt change in one solenoid these coils for some time can compensate its influence on neighboring solenoids. Parameters of compensation coils and magnetic field pulse form generated by coils will be determined at the following stages of investigations as well.

Previous estimations show that compensation coils for effective screening of adjacent to failure blocks have to be about 0.1 of block length and specific number of wraps

approximately the same as in operating blocks. In this case inductance of compensation coils will be about 0.15 of inductance of operating solenoid block. Such coils may be copper made with the same section as superconducting matrix.

Without ferrous solenoids have strong scattering fields. These fields act on measuring apparatuses, diminish freedom of displacement. So without special measures magnetic field is about 0.1 T even at a distance of 1 m from solenoid. Presence of magnetic screen around solenoid sufficiently diminished scattering fields and increase field intensity in aperture up to 20%; this fact diminishes total energy stored in the field. Because of magnetic field in long solenoid is high (up to 6.5 T) and solenoid aperture ranges up to 60 cm, it is appropriate to use magnetic screen common for all solenoids. For diminishing of magnetic field by a factor of 1000 at the distance of 1 m from screen iron screen with thickness not less than 15 cm is required.

In described solenoids as well as in the most part of permanent current solenoids cooling in criostat is accomplished on surface, but inter-block gaps have to be designed for liquid helium flow and output of gaseous phase, because of solenoid length is sufficiently higher than its transverse dimensions and diameter of longitudinal channels displaced along resonator.

From described facts we notice that focusing system of accelerator may be realized on the base of technique developed for set of powerful installations successfully operated at present time. But for final choice of design it is required to solve a number of problems. These problems will be solved at the following stage of investigations.

2.5. Deuteron Linear Accelerator Design

The outline of linac design is shown in the Fig.4.6-1. Accelerator is 30 m in length and contains 14 accelerating resonators (p.1, NN 1-14), superconducting focusing solenoids (p.2), magnetic screen (p.4) and adjustable supports with

adjusting system. The base of massive magnetic screen (screen walls are 100 mm in length) is girder; supports of resonators and criostats with solenoids are placed on it.

Structurally accelerator consists of three modules. Each module contains two resonators placed inside one solenoid. Outer Diameter of each resonator is 400 mm. Inner diameter of "warm" opening of criostat is 600 mm. Resonators of each module are rigidly connected through faces by bolts. RF excitation to resonators is supplied by coaxial feeders (Fig.4.6-1, p.3) through gaps between criostats. Sealing windows are placed outside of magnetic screen. Adjustment of resonators and solenoids is accomplished relative to the base of magnetic screen.

Cylindrical magnetic screen with inner diameter of 1400 mm is knock-down. For mounting it is partitioned into sections in longitudinal and transverse directions.

Resonators, criostats with solenoids are placed on individual adjustable supports and have mechanical decoupling in longitudinal direction. Screen design provides access to all adjusting mechanisms and communication mounting (water, vacuum etc.).

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V

PROTON LINEAR ACCELERATOR
WITH THE ENERGY OF 1 GeV AND CURRENT OF 250 mA

5.1. Principal Scheme of Accelerator

Principal scheme of CW proton linear accelerator is shown in Fig.5.1-1. Accelerating system consists of three accelerating sections with the specific type of accelerating resonators:

- 8 accelerating h-type resonators are used at the section from 0.15 MeV to 20 MeV; its structure is analogous with the structure of deuteron accelerator resonators (see Part 2); they are excited by 1 MW klystrons at the frequency of 350 MHz;

- 5 "long" accelerating DTL-type resonators are used at the section from 20 MeV to 100 MeV; they are excited by 5.5 MW regotrons at the frequency of 700 MHz;

- 55 disc&washer accelerating resonators are used at the third (main) section from 100 MeV to 1000 MeV; they are excited by 5.5 MW regotron at the frequency of 700 MHz.

RF supply system and system of automatic control are designed according to classical scheme [5.1]. Average accelerating rate is 1 MeV/m.

Superconducting solenoids as single type of focusing lenses are used along the whole accelerator; accelerating resonators are placed inside solenoids. As indicated in MRTI works earlier [5.1, 5.2], use of such single scheme of acceleration simplifies solving problems of acceleration and proton beam transport with the current up to 250 mA with the beam losses not higher than 10^{-5} :

- a) high HILBILAC acceptance and high limiting current (700 mA at the frequency of 350 MHz) make it possible to form beam at initial acceleration stage with good longitudinal and transverse characteristics;

- b) one-type focusing provides good matching between different linac parts (HILBILAC-DTL, DTL-HBL);

c) use of superconducting solenoid focusing at HBL part makes it possible to use "long" D&W resonators without its subdivision into sections; absence of sectionalization (in common scheme sections are connected by bridges) sufficiently increase coupling factor in accelerating resonator (AR) (up to 40-50%) and decrease geometrical tolerances sensitivity of AR.

d) change of big number of quadrupole lenses to focusing solenoids decreases sensitivity to random perturbation approximately in order (computing simulations results).

With the use at superior part of linac 5.5 MW regotrons the number of RF supply channels is several times smaller; this fact sufficiently enhanced reliability of accelerator operation.

Main accelerator parameters are listed in the Table 5.1. It is evident that this accelerator is more simple in comparison with linear accelerator described in [5.1].

Table 5.1

**Main Parameters
of CW Linear Proton Accelerator with Superconducting Solenoids
with the Energy of 1000 MeV and Current of 250 mA**

Parameter	Initial Part	First Part	Second Part
Accelerator type	HILBILAC	DTL	D&W
Resonator type	H-resonator with opp.vib.		
Injection energy, MeV	0.15	20	100
Output energy, MeV	20	100	1000
Current, mA	250	250	250
Momentum spread, %	1.2	0.3	0.15
Phase width, degr.	30	20	10
Effective emittance normalized, cm·mrad	0.25	0.3	0.35
Frequency, MHz	350	700	700
Acceleration rate, MeV/m	1	1	1
Number of resonators	8	5	55
Resonator length, m	4-1	12	12

Resonator diameter, m	200	290-255	600-470
Equilibrium phase, degr.	90-30	30	30
Focusing type	SS	SS	SS
Magnetic inductance, T	6.5-5	5	5
Acceptance normalized, cm·mrad	1.2	1.4	1.4
Number of solenoids	4	32	360
Solenoid length, m	7.5-1.5	1-0.5	0.5
Diameter of "warm" solenoid field, mm	400	400	750
Generator type	CW klystron	Regotron	Regotron
RF generator power, MW	1	5.5	5.5
Number of generator	8	5	55

Detail feasibility study of main systems of the linac are presented in the following parts.

5.2 Accelerating System

As indicated above three types of accelerating resonators are used in accelerator.

5.3-1 Accelerating structure of initial part

It is suitable to use structure based on excitation of wave with longitudinal magnetic field in cylindrical resonator, so-called H-resonator, as accelerating structure for proton acceleration from 0.15 MeV. H-resonators were practically taken up and demonstrated high efficiency especially for small relative velocities of particles ($\beta = 0.005-0.1$). As in the case of first version of proton accelerator [5.3] accelerating structure (AS) with opposite vibrators loaded at the end of drift tubes and excited at the H_{111} wave was used as accelerating structure for initial part.

Operating frequency was chosen relatively low and is equal to 350 MHz; it is connected with practical realizable dimensions

of initial cells of structure. According to preliminary calculations it is possible to use this structure for proton acceleration up to 20 MeV.

The possibility of changing of angle between neighboring vibrators from 180° at the last cells (the most long ones) up to the value providing demanded field distribution along structure is used as the tools of tuning of heterogeneous structure cells. Accelerating structure will consists of 8 resonators (AR). The distance between resonators is $\beta\lambda$. Practically resonators are separated only by partitions. Length of some initial cells (period) of first AR is $3/2\beta\lambda$; it is demanded by the possibility of the achievement real longitudinal dimensions of drift tubes from the point of view of manufacturing and heat removal. In this case minimal period is 22.8 mm. All next cells will $\beta\lambda/2$ in length.

Proposed resonator design is as follows. Cylindrical resonator 200 mm in diameter contains drift tubes with the axis coincided with the axis of resonator. Diameter of aperture opening is 10 mm, outer diameter of drift tube is 20 mm. All odd tubes are connected with resonator generatrix and its length are equal to the distance between outer edges of odd drift tubes. Tubes are connected with the plate by radial bars 3-6 mm in diameter. Altitude from structure axis to plate is approximately 30 mm. Channels for circulation of cooling water are deigned in the plate. Each of even tubes are connected with resonator by sector with altering angle (at the initial part of the structure it is approximated to 180°). Channels for water circulation are designed in the sectors as well. The edge even demi-tubes are placed on the end covers of resonator.

The same constructive elements as in the case of first version of proton accelerator discussed in report [5.3] are used for frequency fine-tuning and generation of demanded distribution of accelerating field in the structure.

According to estimations the values of effective shunt impedance are varied in the range from 300-500 MOhm/m to 45 MOhm/m (excepting first periods that are equal to $3/2\beta\lambda$, where shunt impedance is sufficiently smaller).

Complex of codes ISFEL3D [5.4] will be used during design of specific construction of resonator.

Power input in each resonator is accomplished by the same manner as in the case of deuteron linac with the help of coupling loop from face wall (loop is placed in the plane passing through the middle of drift tubes).

Parameters of the first and last resonators of the initial part are listed in the Table 5.2.

Table 5.2

N resonator	1	8
Resonator diameter, mm	200	200
Resonator length, m	4	1
Aperture diameter, mm	10	10
Drift tube diameter, mm	20	20
Nominal value of RF power dissipated in copper, kW	0.01	0.1
Rf power per beam acceleration, MW	0.04	0.74

3.3-2 DTL Accelerating Structure

Standard decision for proton acceleration from 20 MeV up to 100 MeV is accelerating structure with drift tubes, Alvarez-type resonator. Choice criteria are the same requirements as in the case of H-resonator. Operating frequency of second part is 700 MHz. Number of resonator is 5. Because of focusing elements are outside resonators it makes possible: 1) to vary transverse dimensions of resonators and drift tubes in wide range with the aid to achieve maximal value of shunt impedance; 2) there is a possibility of resonator tuning by changing of drift tubes diameters. The length of structure cells (period) is $\beta\lambda$. Resonator lengths are chosen with regard to its excitation by 5.5 MW regotrons.

The following concept of resonator design is proposed. Cylindrical resonators from 290 mm to 255 mm in diameter and

about 16 m in length contain drift tubes fixed by bars on cylindrical surface and placed in the plane passing through generatrix and resonator axis. Aperture opening diameter is 20 mm. Outer diameter of drift tubes is 42.5 mm, bars diameter is 8 mm. Channels for circulation of cooling water are design in bars and drift tubes. From cylindrical shell and face bottoms heat will remove with the help of channels with cooling water placed on the outward surfaces.

Calculated values of effective shunt impedance range from 65 MOhm/m to 45 MOhm/m, RF losses per unit resonator length with accelerating rate of 1 MeV/m range from 16 kW/m to 30 kW/m. Each resonator has 8 RF power inputs. Power input is accomplished by coupling loops from cylindrical wall (loop is in the place passing through generatrix and resonator axis).

Calculated parameters of drift tubes resonator are listed in Table 5.3.

Table 5.3

Resonator diameter, mm	290-255
Resonator length, m	16
Aperture diameter, mm	20
Drift tubes diameter, mm	42.5
Nominal value of RF power dissipated in copper, kW	256-480
RF power per beam acceleration, kW	3.6-3.8

5.3-3 Disc&Washer accelerating structure

It is reasonable to use bi-periodic accelerating structure with discs and washers developed in MRTI as accelerating structure for proton acceleration from 100 MeV to 1000 MeV. This structure was used in main part of proton accelerator of Moscow Meson Facility (MMF) [5.5] as well as in proposed CW proton accelerator discussed in [5.3].

However, operating frequency in MMF is 991 MHz and in

discussed accelerator it is 700 MHz. This fact affects on radiotechnical parameters and geometrical characteristics of the structure. Structural characteristics of resonator including RF power inputs are practically the same.

Because of focusing elements are placed outside of resonator it is not needed to make gaps for its displacement and to use resonance bridge devices; high coupling factor between cells make it possible to use long resonators and fully realized advantages of higher coupling factor in comparison with other bi-periodic structures.

Accelerating system consists of 55 separated resonators from 595 mm to 475 mm in diameter and about 16.4 m in length. Practical realization of resonator design demanded its division onto separated technological sections in a manner like MMF resonators. Length of cell structure (period) is $\beta\lambda/2$.

Calculated values of effective shunt impedance range from 45 MOhm/m to 60 MOhm/m; RF losses per unit length with accelerating rate of 1 MeV/m range from 30 kW/m to 20 kW/m. For first resonators heat regime is most hard; taking into consideration that main part of RF power will release in discs, it is acquit to increase acceleration rate in the first resonators. Calculations were made with the help of AZIMUTH code [5] with additional service (auxiliary) codes simplifying preparation input information and output parameters. Calculated parameters of D&W resonators are listed in Table 5.4.

Table 5.4

Resonator diameter, mm	596-475
Resonator length, m	16.4
Aperture diameter, mm	20
Drift tubes diameter, mm	42.5
Nominal value of RF power dissipated in copper, kW	490-330

5.4 RF System

Accelerator RF system (see block-scheme in Fig.5.4-1) consists of

- HILBILAC RF system,
- HBL and DTL RF system,
- powerfull mastering device (PMD)

3.4-1 HILBILAC RF System

RF system consists of 8 RF channels of amplification (AC) operating at frequency of 350 MHz and feeder system (FS).

For the purpose of unification all channels of amplification are designed with the same RF power of 1300 KW. This RF power is spend to compensation of RF losses in resonator copper, beam acceleration, compensation of RF losses in elements and devices of fed system. RF power reserve of 15-20% is design for operation of system of RF field level automatic control. Klystron is suggested as output device of RF channel of amplification. Modified klystron YK-1350 with operating frequency of 350 MHz and output RF power of 1300 kW used in RF system of accelerator complex LEP-2 [5.6] may serve as prototype of such klystron. Its parameters are as follows:

operating voltage	100 kV
beam current	2.5 A
DC to RF conversion efficiency	65%
current of moduling anode	< 5 A
maximal SWF of load	< 1.2

RF power from klystron output is fed into resonator through coaxial feeder with water cooling 300×130 mm in section. At the section near resonator the section of coaxial feeder is 115×50 mm. There is RF sealing window at this section outside of magnetic screen covering superconducting solenoid. Power output window of YK-1350 klystron may serves as prototype of RF sealing window.

For stable without parasite oscillation operation of RF

channels of amplification with wide range of load changing ferrite circulator is introduced between resonator and klystron output. Circulator must have output-to-input-port isolation (S_{12}) is higher than 20 db, losses in forward direction is lesser than 0.1 db.

Systems of automatic control of RF field phase and amplitude as well as system of fine tuning of resonator frequency are traditional ones for ion linear accelerators [5.1] (see Fig.4.4-1 and Part 4.3).

5.4-2 DTL and HBL RF System

According to structural scheme of accelerator DTL and HBL resonators operate at frequency of 700 MHz and consume RF power of 4 MW for beam acceleration per each resonator. So similar type RF channels of amplification are used for DTL and HBL resonator excitation. Having to regard RF losses in resonator copper, elements and devices of feeder lines, as well as RF reserve of 15-20% for operation of RF field control system, RF power of channel is equal to 5.5 MW. Total number of RF amplification channel is 60, of which DTL RF channels number is 5 and HBL RF channels number is 55.

Simplified block-scheme of amplification RF channel is shown in Fig.5.4-2. In output cascade of RF channel it is supposed to use regotron [5.7] with the following parameters:

output energy	500 kV
current	16 A
RF power of excitation	0.5 kW
number of outputs	8
efficiency	$\geq 70\%$

From each of eight regotron outputs RF power is fed to RF input into resonator through waveguides with rectangular section of 292x146 mm. Each waveguide contains phase control device (PC) for phasing of RF voltage between resonator inputs and ferrite circulator (FC) with output-to-input-port isolation not less than 20 db. RF power inputs are placed between focusing solenoids at the distance of 1/16 of resonator length from face

walls and at distance of $1/8$ of resonator length from each other; it presents conditions for suppression of non-operational types of oscillations. Design of RF power inputs and RF sealing window are as follows. For DTL resonators with diameter not less than 290 mm it is supposed to use coaxial type of RF inputs and RF sealing windows. Power input of YK-1250 klystron operating at frequency of 999 MHz with output power of 400 kW may serve as prototype. Waveguide RF power inputs are used in HBL resonators. So can-type RF sealing window may be used as in waveguide system of LAMPF and MMF.

Preliminary amplifier and systems of automatic control of amplitude (ACA), phase (ACP) and frequency (ACF) are constituents of RF channel of amplification.

System of automatic control of amplitude takes into account characteristic features of regotron operation. Error signal from ACA controls beam current of regotron injector.

System of phase automatic control is traditional one.

Control of phase is accomplished by phase shifter placed at the input of preliminary amplifier (PA). RF voltage of base phase line or RF voltage from transducer of accelerating beam bunches phase may serve as base phase voltage.

In the system of phase automatic control RF signal from resonator and RF signal from RF field transducer in one of eight feeding waveguides are compared in phase detector (PD). Error signal is fed to final-control system.

3.5. Focusing System

Focusing magnetic field along the whole length of accelerator is generated by superconducting solenoids. Solenoid lengths, its number and filling factor are determined by the number of RF inputs into resonators and energy of charged particles. Demanded field distribution in initial part of accelerator is essentially provided by single long solenoid with small technological gaps and at the end of accelerator by system of short isolated solenoids. Maximal inductance of magnetic

field on solenoid axis ranges from 6.5 T to 5 T.

Materials for superconducting solenoids and structural scheme of solenoid-cryostat system are similar to ones described in Part 2.5 for deuteron linac.

Main parameters of superconducting solenoids are listed in Table 5.5.

Table 5.5

Accelerating structure	HILBILAC		DTL		HBL	
Parameter\Solenoid N	1	4	1	32	1	360
Solenoid current, A	2000		1500		1500	
Magnetic field, T	6.5	5	5	5	5	5
Specific number of wraps in central part, 1/cm	26	20	27		27	
Diameter of "warm" field, m	0.4		0.4		0.75	
Outer diameter, m	0.52	0.48	0.52		0.78	
Solenoid length, m	7.5	1.5	1	0.5	0.5	
Section of matrix with 50% filling, mm ²	2×3.5		2×3.5		2×3.5	
Superconductor material alloy	NbTi		NbTi		NbTi	
Matrix material	Cu		Cu		Cu	
Maximal filling factor	0.8	0.5	0.5	0.2	0.2	
Structural current density, A/mm ²	150		100		100	
Number of blocks 0.5 m in length	15	3	2	1	1	
Inductance, H	11	1.3	1.44	0.72	2.76	
Storage energy, MJ	22	2.5	1.6	0.8	3.1	
Energy storage in block, MJ	1.5	0.9	0.8	0.8	3.1	
Heat losses, W	15	0.33	0.16	0.08	0.15	

Focusing system of initial part (HILBILAC) is similar to system described in Part 4.5.

Focusing system of DTL has a set of distinctions:

- technological gaps with gradually increasing length from 0.78 m to 2 m along linac are designed for RF power inputs;

- for effective usage of helium and nitrogen criostats are unified to crio-modules; in this case helium and nitrogen supply into criostats is accomplished sequentially;

- for screening of scattering magnetic fields focusing system is placed inside ferrous screen about 15 cm in thickness.

Because of efficiency of radial screens is determined by its displacement, solenoid aperture and screen thickness, so according estimations the use of radial screens is effective in the second part of DTL magnetic system. In this case requirements to correcting coils are not so strict.

Magnetic system of main accelerator part consists of separated solenoids. Solenoids with inductance of $B = 5 \text{ T}$ are displaced along accelerator with period of 2.5 m.

The problems connected with provision of mechanical and neat stability of this part of magnetic system are not so vital and may be solved by methods used in systems described above. Because of weak inductive coupling between coils of HBL magnetic system the problems connected with ponderomotive forces and electromagnetic avalanche are not so hard.

Each solenoid is design similar to previous one with correction of the field at the ends. Solenoid cooling is accomplished over the entire surface without additional channels.

Criostats are connected to crio-modules similar to ones of second part of DTL magnetic system.

Magnetic screens for each solenoids are designed separately with walls 15 cm in thickness. It is determined by the fact that solenoids are separated from each other for a distance of several meters. Presence of face screens additionally decreases magnetic interaction between neighboring solenoids.

Solenoids of this part are fixed on common support girder.

In conclusion we note that accelerator focusing system may be realized on the base of technologies successfully used at presence. However, final choice of construction of focusing system elements demands the decision of the following problems: calculation of design and parameters of compensation coils, decrease of screens number in criostat, crio-system

exploitation, development of specific system of solenoids protection. These problems will be solved at the following stage of investigations.

3.6. Accelerator Design

Design of initial part of accelerator with the energy of 20 MeV (HILBILAC) is similar to ones of deuteron accelerator described in Part 2.6.

The first part of accelerator (20 MeV - 100 MeV) consists of five resonator with drift tubes, each of them excited at the frequency of 700 MHz from one regotron with output power of 5 MW. Design of first module consisted of one resonator with drift tubes 1 and eight superconducting solenoids 2 is shown in Fig.5.6.1. Resonator and solenoids are placed inside magnetic screen 3 of composite construction; it serves as girder for resonator and solenoids justification. Resonator is excited from regotron through eight waveguides with pressure windows 4.

Main accelerator part (100 MeV - 1000 MeV) consists of 55 similar modules. Design of one module is shown in the Fig.5.6-2. Module consists of one D&W resonator 1 consisted of some rigidly fasten together section, four superconducting solenoids 2 with magnetic screen 3 and device for beam parameters measurements 8. Resonator is connected with device by flexible sealing unit 10. Resonator is 12 m in length. Resonator is fixed on girder.

Resonator is excited at frequency of 700 MHz from regotron through eight waveguides with pressure windows 11. High-vacuum pumping is accomplished through branch pipe 12.

Support girder 4 is carried at one end by adjusting system 5 and at other end by next girder with the help of horizontal rod imputing into special erring. Similar design of support girders was used in linear accelerator of MMF. Adjusting is accomplished relative to support girder through mechanism 7 and superconducting solenoids through mechanism 6.

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a)

b)

Fig.1.1.
Harmonic coefficients $F_{k0}(x, \gamma)$ for $\gamma = 0.1, 0.2, \dots, 1$.

Fig.2.1.
Energy characteristics of beam
in the channel with constant amplitude, $\alpha = 0$.

Fig.2.2.
Energy characteristics of beam
in the channel with constant amplitude, $\alpha = 0.15$.

Fig.2.3.
Energy characteristics of beam
in the channel with constant amplitude, $\alpha = 0.3$.

Fig.2.4.
 Energy characteristics of beam
 in the channel with constant amplitude, $\alpha = 0.6$.

Fig.2.5.
Energy characteristics of beam
in the channel with increasing amplitude, $\alpha = 0.07$.

Fig.2.6.
 Energy characteristics of beam
 in the channel with increasing amplitude, $\alpha = 0.6$.

Fig.2.7.
Energy characteristics of beam
in the channel with increasing amplitude, $\alpha = 1$.

Fig.2.8.
Transition into steady state of bunch length and Coulomb field harmonics
through 8 periods of oscillations in increasing field, $\alpha = 1$.

a)

b)

Fig.2.9.
Comparison of equivalent bunch length
in constant and increasing fields, $\alpha = 0$.

a)

b)

Fig.2.10.
Comparison of equivalent bunch length
in constant and increasing fields, $\alpha = 0.5$.

a)

b)

c)

Fig.2.11.
Comparison of harmonic spectrum of Coulomb field, $\alpha = 0.3, 0.6, 1.2$.

Fig.3.1.
Phase portrait of the beam
matching without regarding to bunching
after 1/4 period of longitudinal oscillations.

Fig.3.2.
Harmonic factors $G_{k0}(x, \gamma)$ for $\gamma = 0.1, 0.2, \dots, 1$.

a)

b)

c)

Fig.3.3.
Charge distribution and radial component of Coulomb field distribution
as a function of R_b/R_a ($R_b/R_a = 0.15, 0.5, 0.95$)
for beam with phase width of 180° .

Fig.3.4.
 Phase portrait of output beam of initial part of accelerator.
 Output energy - 2 MeV, initial emittance - 0.

Fig.3.5.
 Beam phase and radial trajectories of accelerator initial part.
 Energy 0.1 - 2 MeV, initial emittance - 0.

Fig.3.6.
Phase portrait of output beam of initial part of accelerator.
Output energy - 2 MeV, initial emittance - 0.1π cm-mrad.

Fig.3.7.
 Beam phase and radial trajectories of accelerator initial part.
 Energy 0.1 - 2 MeV, initial emittance - 0.1π cm·mrad.

Fig.4.1-1.

Fig.4.3-1.
HILBILAC cavity construction.

Fig.4.4-1.

Fig.4.6-1.

Design of deuteron linear accelerator.

energy - 40 MeV

- 1 - accelerating resonator (AR) (N 1 - N 14),
- 2 - superconducting solenoids (SS), 3 - RF feeder, 4 - magnetic screen,
- 5 - superconducting solenoid of transport channel, 6 - supports,
- 7 - pipe branches of vacuum system.

ACCELERATOR MAIN DESIGN

1000 MeV, 250 mA CW PROTON LINAC

Fig.5.1.-1.

Fig.5.4-1.

Fig. 5.4-2.

Fig.5.6-1.
Design of first module of accelerator initial part.

Fig.5.6-2.
Design of standard module of accelerator main part.